IMPACT OF MOSQUE GEOMETRY ON ITS ACOUSTICAL PERFORMANCE.

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Abstract. The mosque as an important building type of Muslim architecture has evolved to meet religious needs. A variety of different worship activities happen within this multifunctional public space; these different activities have different acoustical requirements. This paper aims to emphasize the impact of the mosque geometry on its acoustical design to maintain good acoustic quality. In this study, the acoustical characteristics of typically constructed contemporary mosques without domes and with four various geometric configurations in Saudi Arabia had been investigated by means of acoustic measurements. Speech Transmission Index (STI), Clarity (C80), and Definition or Deutlichkeit (D50) have been tested. We found that the best acoustical performance could be obtained by using the 1:2 rectangle and square geometries.

1. Introduction

The mosque as an important building type of Muslim architecture has evolved to meet religious needs. A variety of different worship activities happen within this multifunctional public space; these different activities have different acoustical requirements. As in many other religions, worshippers usually need solitude, while at other times they want to feel absolute unity with the others presence. Acoustics is one of the basic means of creating different effects [1]. The architect Sinan's mosques have been studied in the European Commission Fifth Framework INCO-MED Program called "Conservation of the Acoustical Heritage by Revival and Identification of Sinan's Mosques' Acoustics (CAHRISMA) [2]. The goal of this project was the identification, revival and conservation of Hybrid Architectural Heritage (visual and acoustical heritage) in a real-time virtual environment. Sinan's Mosques and Byzantine Churches were well known of their good acoustical qualities. They were chosen as case studies to be utilised for the realisation of this objective [2].

Fausti, Pompoli and Prodi compared the acoustics of mosques and churches [3]. They found that reverberation time, in the unoccupied condition, is very long, giving them a unique feeling of majesty. In another study, Karabiber and Erdogan [4] compared the ancient mosque of Kadırga Sokullu Mehmet Pasa with a recent one, Sisli Merkez. They concluded that although there was no great difference between the total sound absorption of the spaces, the acoustics in the ancient mosque was better. Sinan’s important mosques have been analyzed in other studies besides the CAHRISMA project (Kayili, 2002; Topaktas, 2003). Kayili (2000) [5,6].

The Architectural works of Sinan are among the most successful applications of acoustic science. Sinan designed a total space for the interior of the mosque, not divided into spaces and reduced to the size of room. The interior volume of the Selimiye Mosque is approximately 75,000 m3 and, naturally, it is evident that the problem of the power of the sound source will arise. To overcome this problem, Sinan placed the muezzin's mahfil exactly in the centre of the total space. The dome and also cavity resonators are directly above the sound source [7].

The acoustical quality of the mosques has also been discussed in the literature [1-8]. Mosque design is mainly influenced by worship considerations; three distinct activities are carried out in a mosque, either individual or in-group:

- The first is prayers, either individually or in a group led by a leader, the Imam.
- The second is attendance at a sermon being delivered on its own or within the Friday noon prayers.
- The third is listening to or reciting some verses from the Holy Quran.

All these activities require a high level of speech audibility and intelligibility. To ensure good listening conditions of the acoustical needs which must be considered in the design phase [8].

In summary, there are three distinct acoustical requirements for mosques:

- Audibility of the prayer orders of the Imam (prayer leader)
- Recognizable sermon of the preacher
- Listening to or joining in the recital of the musical versions of the Holy Quran.

Thus, intelligibility of both speech and other sounds is extremely important, especially important for holy tones that must be both spacious and effective. Several acoustical parameters govern speech audibility, intelligibility and spaciousness of sound; the parameters usually employed in the acoustical analysis of mosques are reverberation time, sound pressure level distribution and sound transmission index.
The acoustical characteristics of typically constructed contemporary mosques without domes in Saudi Arabia had been studied by means of reverberation time (RT) and the early decay time (EDT) field measurements [9]. This study had been taken in varies representative mosques of different forms and architectural features in order to characterize their acoustical quality and to identify the impact of its prayer hall form on their acoustics performance. It is found that the 1:2 rectangle mosque geometry negatively impacted sound fields in the front rows.

In this study, four types of Mosques will be tested to evaluate and predict the acoustical quality of Mosques prayer halls. Many acoustic parameters, Speech Transmission Index (STI), Clarity (C80), and Definition or Deutlichkeit (D50), have been tested by means of field measurements.

1.1 WORSHIP CONSIDERATIONS AND THEIR INFLUENCE ON SPATIAL ARRANGEMENT

The distinct worship activities inside mosques include praying, public speeches, preaching, lecturing, and *Qur'an* recitations. The activities are performed by people either individually or in conjunction with others. The activities may be categorized into one of two primary worship modes: prayer mode or preaching mode. In prayer mode, all mosque users are either standing, bowing, or prostrating, always on the same floor level, and aligned in rows parallel to the *Qibla'* wall (front wall), with the *Imam* (speaker) facing away from listeners. In preaching mode, the listeners are sitting on the floor in rows parallel to the Qibla' wall, while the Imam is standing on a four-step high platform (*minbar*) facing the listeners. The worship activities generally require adequate speech audibility and intelligibility. The leader or Imam generally stands in front of the gathering, near the *mihrab*, a distinct area provided for him. General mosque orientation is based on the position of the mihrab, which is intended to face the Qibla' (a cubical building at Mecca, Saudi Arabia). Prayer from the Imam is to address the gathering from his position. For certain prayers such as *Jumma* (Friday) prayers, the Imam addresses the gathering with preaching, or *khutba*, from the minbar, which in general is considered to be high enough for the gathering's visibility (see Figure1).

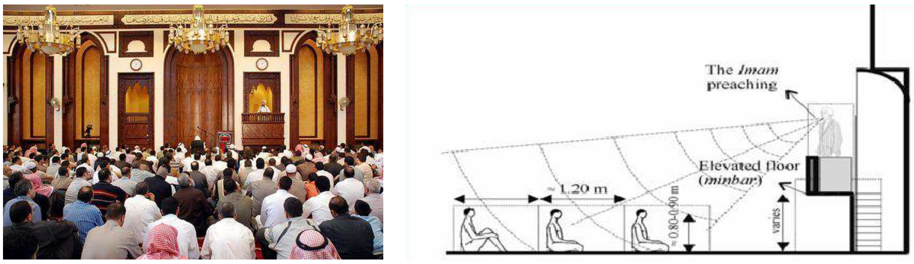

Figure 1. Preaching inside the prayer hall.

The congregational capacity of the mosque is usually determined by the floor area divided by the area required per worshipper to perform various prayers motions. This is approximately 0.80 x 1.2 = 0.96 m^2 (Figure 2).

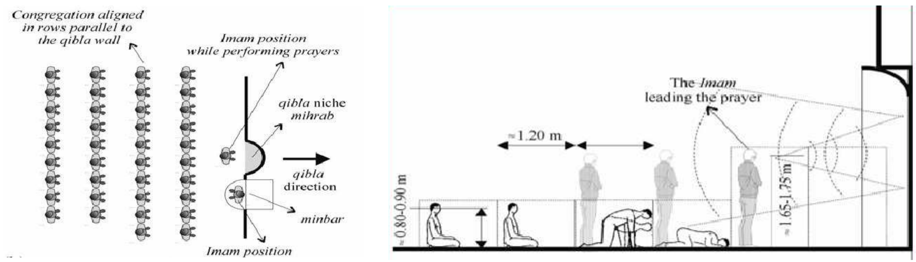

Figure 2. Praying inside the prayer hall, the Imam is leading the prayer followed by the worshippers.

Most parts of the interior of mosques are intended to be finished with acoustically reflective materials such as painted plaster and tile (both marble and ceramic). However, the floor area was to be covered with heavy carpet. The ceilings, including the dome, will be finished with painted plaster and ornamentation. Arches made from concrete and finished with painted plaster will be used as joint elements between the columns to strengthen the construction and to provide interior decorative elements.

1.2 PRAYER HALL

The prayer hall, also known as the Musalla, rarely has furniture; chairs and pews are generally absent from the prayer hall so as to allow as many worshipers as possible to line the room. Some mosques have Arabic calligraphy and Qur'anic verses on the walls to assist worshippers in focusing on the beauty of Islam and its holiest book, the Qur'an, as well as for decoration. Usually opposite the entrance to the prayer hall is the qiblah wall, the visually emphasized area inside the prayer hall. The qiblah wall should, in a properly oriented mosque, be set perpendicular to a line leading to Mecca, the location of the Kaaba. Congregants pray in rows parallel to the qiblah wall and thus arrange themselves so they face Mecca. In the qiblah wall, usually at its centre, is the mihrab, a niche or depression indicating the direction of Mecca. Usually the mihrab is not occupied by furniture either. Sometimes, especially during Friday prayers, a raised minbar or pulpit is located to the side of the mihrab for a khatib or some other speaker to offer a sermon (khutbah). The mihrab serves as the location where the Imam leads the five daily prayers on a regular basis. Most of mosques have typically a simple rectangular form, walled enclosure with a roofed prayer-hall. The long side of the rectangle is always oriented towards the holy mosque in Makka and to its right an elevated floor (Minbar) is used by the Imam to deliver the religious "Friday" speech preceding the prayers. Figure3 illustrates the congregation performing daily individual or group prayers and congregation listening to Friday speech. Interior finishing materials of mosques are varying from one country to another. However, mosque walls are commonly finished with painted plaster. Wall wainscots are sometimes covered with marble tiles or wooden boards or panels tongued and grooved to compose a vertical pattern. The floor area is always carpeted. Plastered and painted concrete ceilings with simple to elaborate decorations and /or inscriptions are commonly used. Depending on the climatic conditions, the mosque may be equipped with an air conditioning system, in concert with some ceiling fans.

2. Methodology

Religious preference is higher for those praying in the first rows compared to late arriving individuals. Hence first rows are preferred to be longer or at least equal to the subsequent remaining ones. As shown in figure 3, majority of mosques in eastern province in KSA have square, rectangular 1:2 and 1:4 ratio and golden section 1:1.6 ratio plans with a long side perpendicular to the direction of the Qibla. These forms were acoustically studied. These prototypes can be considered to be medium-size, community mosques with a prayer hall plan of approximately 1600.0 m2 and 4.00 clear heights and without domes. Table 1 presents the prayer halls geometric information of the proposed mosques. Table 2 shows the intern finishing materials of the selected mosques.

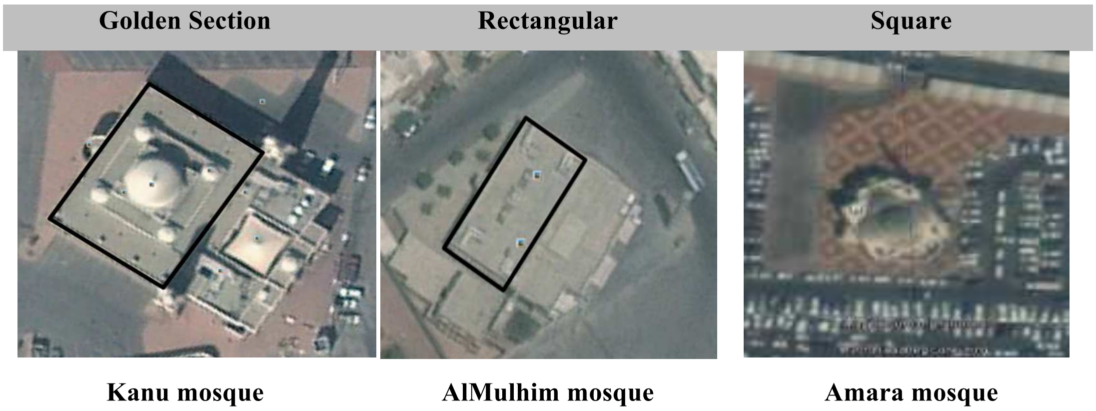

Figure 3. Geometry of mosques in eastern province, KSA

Mosque Form	**Dimensions W, L, H**	**Floor Area m^2**	**Volume m^3**
Rectangular 1:2	14.15 x 28.30 x 4.00	400.44	1601.76
Rectangular 1:4	10.00 x 40.00 x 4.00	400.00	1600.00
G. Section	15.81 x 25.32 x 4.00	400.30	1601.20
Square	20.00 x 20.00 x 4.00	400.00	1600.00
	Mean	***400.00***	***1600.00***
	Standard deviation	0.24	1.00

TABLE 1. Geometric information of mosque shapes.

Surface	Material
Walls 1m &Mihrab	Cladding of Marble Tiles
Walls	Painted plaster surfaces on brick, double glazing windows
Floor	Carpet heavy on concrete
Corridors	Marble

TABLE 2. The intern finishing materials of the selected mosques.

The congregation (worshippers) is performing the prayer behind the Imam who is reciting in a standing position facing the Qibla niche using his raised voice. It is natural that persons delivering speech without the aid of Electro-acoustic sound system tend to raise their voice.

The background noise in the mosques is measured. The worshippers are assumed to be also standing listening to the Imam as is usually the case during performing the “Daily” prayers. Their ear height is taken to be 1.65 m from the floor. Measurements had been realized when the mosque is assumed empty. Figure 4 demonstrates the positions of Sources and receiver points for all configurations (44 receiver points for the rectangle form and 49 receiver points for square form).

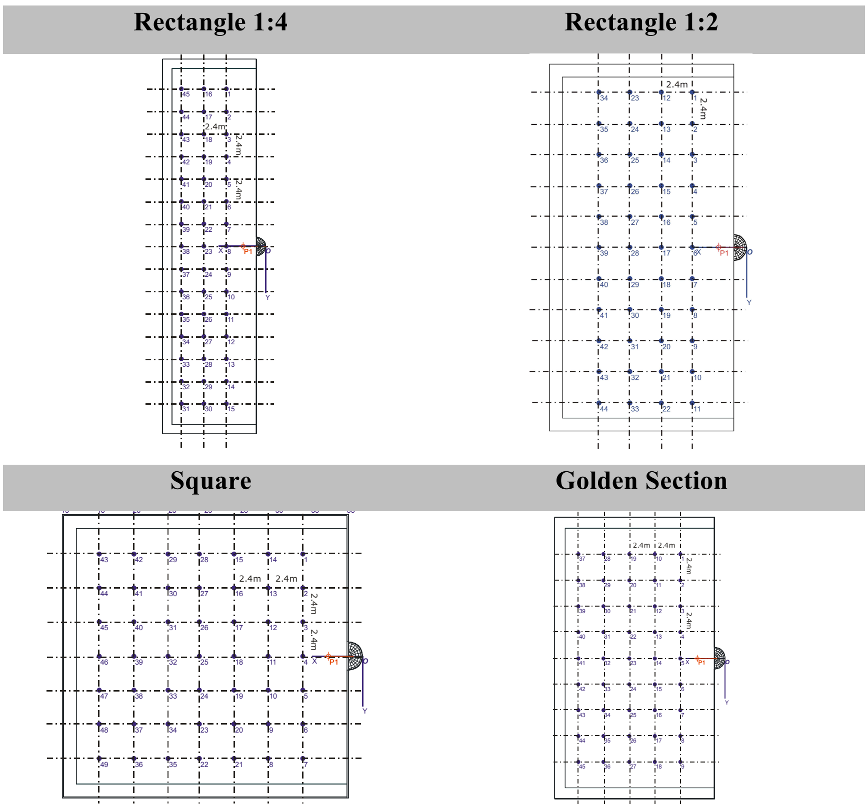

Figure 4. Sound Source and receiver point’s locations.

Sound quality parameters had been measured using DIRAC Room acoustic system, B&K building acoustic analyzer type 2250, a B&K power amplifier type 2716, a reference Omni Power Sound Source Types 4292 and ½ inch B&K microphone type 4134. Measurements had been carried out, in octave bands, for the frequency range 100Hz to 8 kHz. Measurements of the STI had been performed using B&K speech transmission meter type 3361. The transmitter type 4225 had been located at the position of Imam on the Minber, while the receiver type 4419 had been moved around, following the prearranged grid points.

3. Results and Discussion

3.1 DEFINITION (D50)

Definition is the measure derived from the ear’ s response to consecutive impulses; it characterizes the ratio of effective energy to the total energy in an impulse response up to 50ms. There is a good relationship between definition and speech intelligibility. The D50 parameter (Definition or Deutlichkeit) is the early to total sound energy ratio and expressed in percentage. It is defined as:

$$D_{50} = \frac{\int_0^{0.050s} p^2(t)dt}{\int_0^{\infty} p^2(t)dt}$$

This parameter should be greater than 20% to satisfy both music and speech performances (Templeton, 1993).
Figure 5 and 6 present the D50 values obtained by all forms at 1kHz. For the 1:2 rectangle form, it is found that D50 varies between 30% and 70%. For the 1:4 rectangle, square and golden section forms, D50 varies between 30% and 65%.
Generally, D50 Values are acceptable for points that are closer to the mihrab. The decreasing the distance between the source and the receivers the increasing the D50 values. This is probably caused by the first reflections of the mihrab surface and the ceiling.

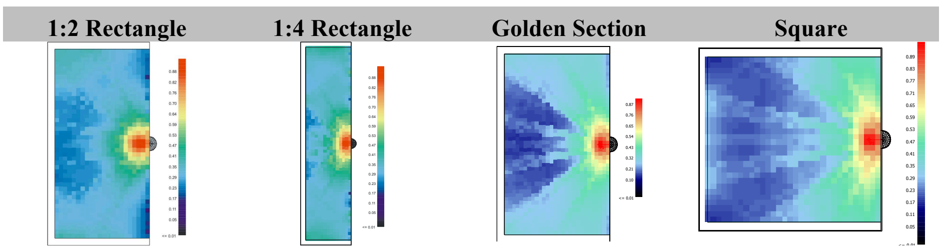

Figure 5. Cartography of Definition (D50) for the all mosque geometries when the mosque is assumed empty at 1kHz.

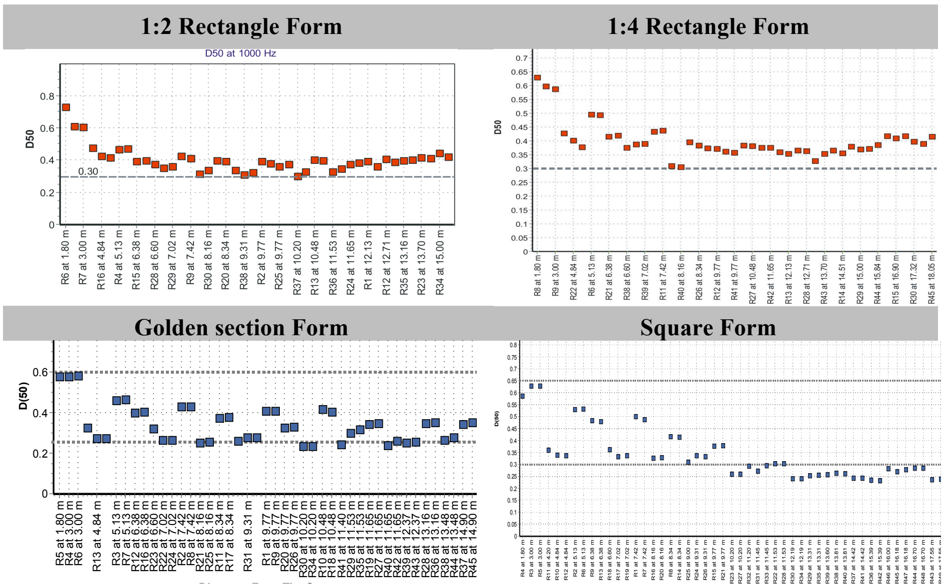

Figure 6. Definition (D50) for all mosque geometries at 1kHz as a function of distance from Imam position.

When background noise is not disturbing, the subjective speech intelligibility is often described by Definition or Deutlichkeit, denoted D or D50, defined as the ratio of the early-received sound energy (0-50ms after direct sound arrival) to the total received energy. This is a straightforward measurement of an impulsive sound from a pistol or other source. It is measured by taking the energy in an echogram during the first 50 to 80msec and comparing it to the energy of the entire echogram. This compares the direct sound and early reflections, which are integrated by the ear, to the entire reverberant sound. There is a good relationship between definition and speech intelligibility. Because of the short distance between the source and the back wall, the 1:4 ratio achieves a good D50. In general, all geometries have acceptable D50 values (see figure 7).

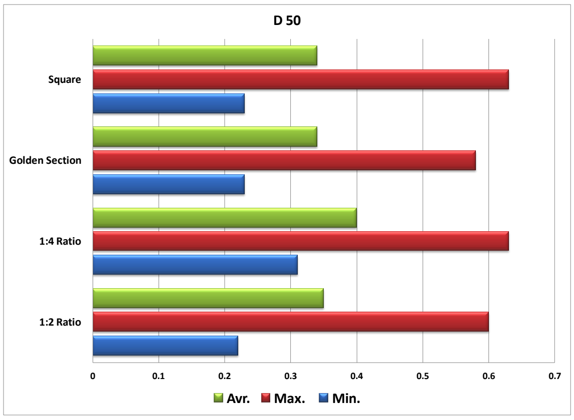

Figure 7. Average, Minimum and Maximum D50 values obtained by all geometries at 1kHz.

3.2 CLARITY (C80)

Clarity is defined technically as the ratio of early sound energy (arriving within 80ms of direct sound) to late or reverberant sound energy (arriving more than 80ms after the direct sound). This quality characterizes the separation in time of sounds from individual instruments or groups of instruments. This parameter must be within certain limits if the musical details are to be heard. In general, a satisfactory acoustical space should have clarity between -2 and +2 dB to satisfy both music and speech criteria, and between -1 and +3 dB for choral music (Kuttruff, 1991). The C50 parameter (Clarity or Klarheitsmass) is the early to late arriving sound energy ratio. It is defined as:

$$C_{50} = 10\log\left(\frac{D_{50}}{1-D_{50}}\right)$$

Clarity expressed in dB. It is common practice to calculate this parameter also over 80ms (C80). The user can set this time interval (C custom).

Figures 8 and 9 shows the C80 values for all forms. In general, the values obtained are suitable for both music and speech. C80 values are within the acceptable range at most of the receiver points located closer to the mihrab. This indicates an adequate distribution of early reflections in these receiver locations. The results of 1:4 rectangle form demonstrates that the C80 values obtained by receiver points located at the back of Imam, points 8, 28 and 38, and points located at the ends of rows are suitable for choral.

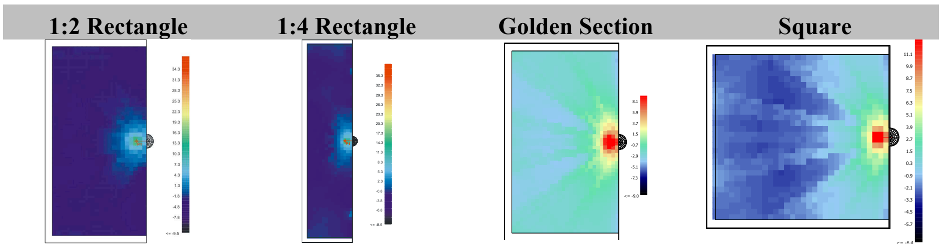

Figure 8. Cartography Clarity (C80) for all mosque geometries when the mosque is assumed empty at 1kHz.

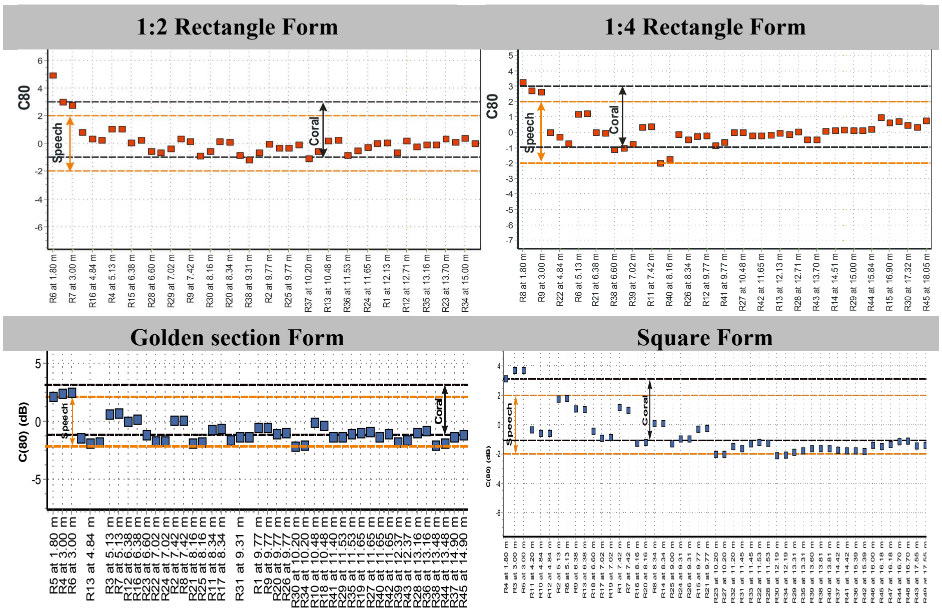

Figure 9. Clarity (C80) for the 1:2 rectangular mosque geometry at 1kHz as a function of distance from Imam position.

Clarity, measured in decibels, is sometimes defined as the difference between the sound energy in the first 80msec, and the late reverberation energy arriving after the first 80msec. In some cases, a C80(3) value is used, which averages clarity at 500; 1000; and 2000 Hz. In large halls, the good value of C80(3) must be between −3 and +1 dB. As shown in figure 10, the best C80(3) value is obtained by 1:2 ratio, while the worst value is obtained by the 1:4 ratio.

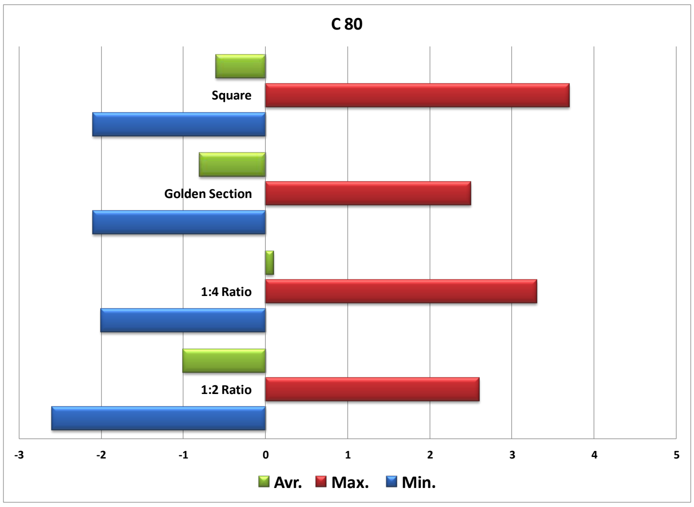

*Figure 10.*Average, Minimum and Maximum C80(3) obtained by all geometries.

3.3 SPEECH TRANSMISSION INDEX (STI)

STI is directly related to speech. To ensure good speech intelligibility, the envelope of the signal should be preserved, allowing the various frequency bands to contribute to speech quality.

Measurements of the RASTI, STI 500Hz and STI 2kHz had be performed using B&K speech transmission meter type 3361. The transmitter type 4225 will be located at the position of imam, while the receiver type 4419 will be moved around, following the prearranged grid points.

STI	0 - 0.3	0.3 - 0.45	0.45 - 0.6	0.60 - 0.75	0.75 - 1.0
Quality	Unintelligible	Poor	Fair	Good	Excellent

TABLE 3. The Speech Transmission Index (STI) is a machine measure of intelligibility whose value varies from 0 (completely unintelligible) to 1 (perfect intelligibility).

STI is directly related to speech. To ensure good speech intelligibility, the envelope of the signal should be preserved, allowing the various frequency bands to contribute to speech quality.

Speech Transmission Index (STI) for the 1:2 rectangular mosque geometry as a function of worshippers rows is presented in figure 11. STI is around 0.20, which is considered unintelligible. The best values have been found at locations just around the source or imam and at the 1st row.

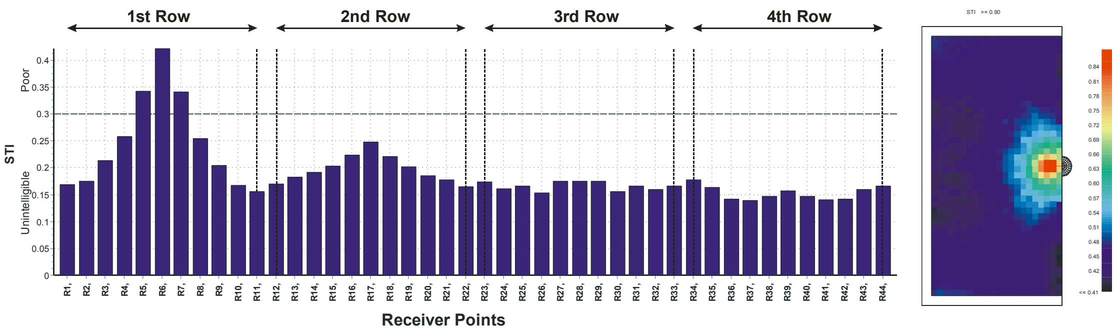

Figure 11. Speech Transmission Index (STI) for the 1:2 rectangular mosque geometry as a function of worshippers rows.

Speech Transmission Index (STI) for the 1:4 rectangular mosque geometry as a function of worshippers rows is presented in figure 12. We found that STI values range between 0.40 and 0.55, which is considered poor. The best values have been found at locations just around the source or imam and at the 1st row, where the STI values are fair.

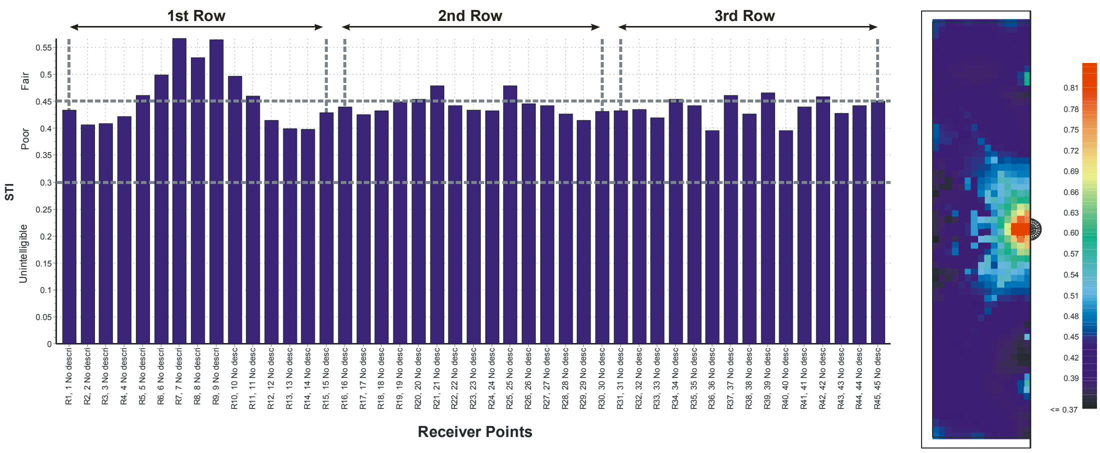

Figure 12. Speech Transmission Index (STI) for the 1:4 rectangular mosque geometry as a function of worshippers rows.

The STI values obtained by the golden section mosque geometry are presented in figure 13. We noticed that STI values range between 0.33 and 0.55, which is considered poor and fair. The best values have been found at locations just around the source or imam and at the 1st row, where the STI values are fair.

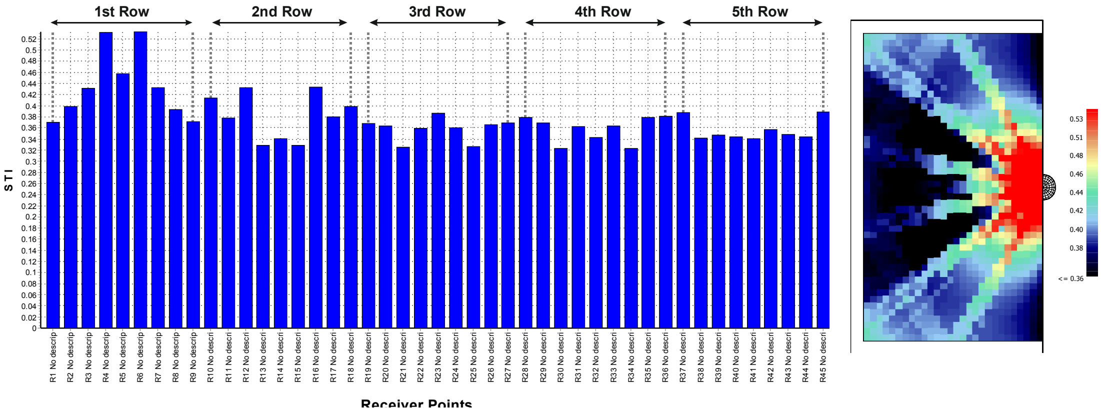

Figure 13. Speech Transmission Index (STI) for the golden section mosque geometry as a function of worshippers rows.

As shown in figure 14, STI values obtained by the square geometry range between 0.4 and 0.65. STI is considered poor and fair. As the pervious cases, the best values have been found at locations just around the source or imam and at the 1st row, where the STI values are considered as fair.

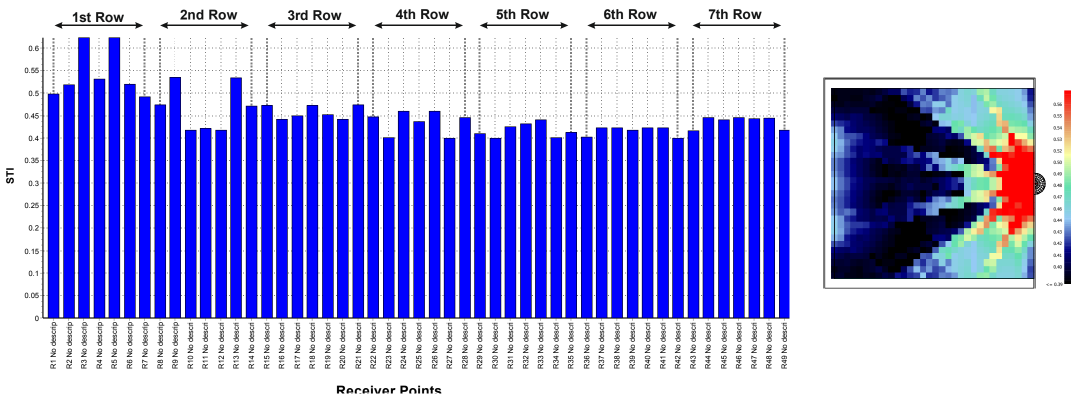

Figure 14. Speech Transmission Index (STI) for the square mosque geometry as a function of worshippers rows.

Figure 15 shows the STI values obtained by all geometries. We can observe that the best value can be obtained by the square and 1:2 ratio where STI considers as fair.

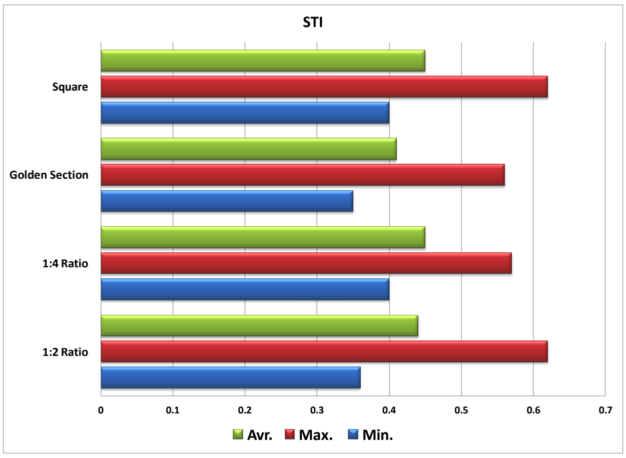

Figure 15. Average, Minimum, and Maximum STI values obtained by all geometries.

4. Conclusion

In this study we evaluated the acoustical performance of prayer hall geometries. We found that the best acoustical performance can be obtained by using the 1:2 rectangle and square geometries. In general, this investigation carried out in this study is expected to help architects to understand better the effect of early architectural design decisions pertaining to the space and form of the mosque on its acoustics. The spatial distribution of many sound quality indicators can be visualized and assessed. It can also assist the design and installation of sound reinforcement systems in terms of number of loudspeakers required, their directivity, and relevant locations to overcome insufficient sound levels or poor audibility hindering speech intelligibility.

References

[1] KARABIBER, Z. G, 1999, Acoustical problems in mosques: A case study on the three mosques in Istanbul. *Forum Acusticum, Berlin*, CDROM, 4 pgs.

[2] YUKSEL, Z.K., BINAN, C. UNVER, R., 2003, A research project in the intersection of architectural conservation and virtual reality: CAHRISMA". *In 19th International Symposium CIPA*. Antalya, Turkey: Technical University of Istanbul.

[3] FAUSTI, P., POMPOLI, R., PRODI, N., 2003, Comparing the acoustics of mosques and Byzantine churches". *19th International Symposium CIPA*. Antalya, Turkey: Technical University of Istanbul.

[4] KARABIBER, Z., ERDOGAN, S., 2002, Comparison of the acoustical properties of an ancient and a recent mosque. Forum Acusticum, Spanish Acoustical Society (SEA), Seville, Spain.

[5] KAYILI, M. A., 2002, Da geleneksel akustik sistemler ve Mimar Sinan uygulamalar, (Anatolian traditional acoustic works and works done by Sinan the Architect). *6th National Acoustical Congress TAKDER*, 26-28 October , 233-238. Antalya, Turkey.

[6] TOPAKTAS, I.L, 2003, Acoustical properties of classical Ottoman mosques: Simulation and measurements. *PhD thesis, Department of Architecture, Middle East Technical University*, Ankara.

[7] KAYILI, M., 2007, Acoustic Solutions in Classic Ottoman Architecture, *Foundation for Science Technology and Civilization*; Manchester, England September.

[8] ABDOU, A.A., 2003, Measurement of acoustical characteristics of mosques in Saudi Arabia. *The Journal of Acoustical Society of America*, 113(3), 1505-1517.

[9] HOSSAM ELDIEN., H., AL QAHTANI, H., 2012, The acoustical performance of mosques' main prayer hall geometry in the eastern province, Saudi arabia. *Acoustics 2012*, Nantes.